

## REPORT DOCUMENTATION PAGE

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) 22 MARCH 2009		2. REPORT TYPE Final		3. DATES COVERED (From - To) 01 MAY 2007 to 31 DEC 2008	
4. TITLE AND SUBTITLE AEROSOL IMPACTS ON CIRRUS CLOUDS AND HIGH-POWER LASER TRANSMISSION: A COMBINED SATELLITE OBSERVATION AND MODELING APPROACH				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER FA9550-07-I-0408	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) DR. KUO NAN LIOU UNIV OF CALIFORNIA				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) MS. KRISTEN LUND UNIV OF CALIFORNIA LOS ANGELES, CA 90095				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AF OFFICE OF SCIENTIFIC RESEARCH 875 NORTH RANDOLPH STREET ROOM 3112 ARLINGTON VA 22203				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT UNLIMITED					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The AF anticipates fielding the ABL in the near future and needs to account for all the atmospheric conditions, such as cloud crystals, which would impede its successful operation. The objective of this additional work basic research effort is to provide additional characterization of the optical properties of cirrus clouds (particularly the ice crystals which form within these clouds at night) together with an improved prediction of the deleterious reflections these crystals provide of laser beams which propagate through them. The PI and his team will analyse the data collected from several new experimental campaigns and then improve/update their laser beam propagation simulation code in light of this analysis.					
15. SUBJECT TERMS <div style="text-align: center; font-size: 2em; font-weight: bold;">20090429212</div>					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON DR. KUO NAN LIOU
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code) 310-825-1217



Joint Institute for Regional Earth System Science and Engineering  
University of California, Los Angeles  
9258 Boelter Hall  
420 Westwood Plaza  
Los Angeles, California 90095-7228

March 22, 2009

Dr. Arje Nachman  
Air Force Office of Scientific Research  
4015 Wilson Blvd, Mail Room 713  
Arlington, VA 22203

Subject: Final Report for AFOSR Grant FA9550-07-1-0408, "Aerosol Impacts on Cirrus Clouds and High-Power Laser Transmission: A Combined Satellite Observation and Modeling approach"  
Covering period: 05/01/07-12/30/08

Dear Dr. Nachman:

During the grant period, we have focused on two lines of original research: (1) analysis of satellite data to understand the relationship between dust and cirrus in specific regions, an uncharted research area in the atmospheric sciences discipline; and (2) use of a regional weather forecast model for cirrus cloud simulation and prediction to support the overall ABL operation. Below are our specific accomplishments.

#### **Satellite data analysis to investigation dust-cirrus interaction**

We conducted a study of the aerosol indirect effect on cirrus cloud formation by using available data from Moderate Resolution Imaging Spectroradiometer (MODIS) on board the NASA Terra and Aqua satellites. We examined MODIS data covering regions of frequent dust outbreaks in East Asia, Middle East, and West Africa, and identified a number of scenes containing dust/aerosols and clouds based on the technique of cloud-mask and visual inspection. Cloud and aerosol optical depths and particle sizes inferred from MODIS for selected domains were analyzed, and the ice water path and ice and dust particle number concentrations were subsequently derived. The selected domains in this study were divided into a number of sub-grids to develop statistical correlations between the sub-grid mean cirrus cloud and dust parameters and to investigate variability and physical significance of these correlations. Our satellite data analysis was divided in three parts as follows:

(1) We first investigated the dust aerosol indirect effect on ice clouds formed at the top of a transported dust layer. We based our investigation on a prominent case detected by the Pulse Detecting Lidar (PDL) during the 2002 Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE) in the southwest coast of Florida, an experiment to study high-level clouds and aerosols. We analyzed the MODIS/Aqua data collocated with the PDL ice cloud detection on July 29, 2002. To obtain physical understanding between dust and ice cloud interactions, we carried out a number of correlation studies using the following parameters determined from the MODIS satellite product: cloud optical depth vs. aerosol optical depth; cloud particle size vs. aerosol optical depth; ice water path (*IWP*) vs. aerosol optical depth; and



ice particle number concentration ( $N_i$ ) vs. aerosol number concentration ( $N_a$ ). The number concentrations  $N_i$  and  $N_a$  vary between 0 and 4  $\text{cm}^{-3}$  and between 20 and 80  $\text{cm}^{-3}$ , respectively, and compare reasonably with those determined from in-situ measurements. Based on linear fittings of the correlated data points, cloud optical depth and *IWP* generally increases with aerosol optical depth, whereas cloud effective particle size decreases with increasing aerosol optical depth. Also, cloud number concentration  $N_i$  increases when dust number concentration  $N_a$  increases. The estimated aerosol indirect effect (AIE) index determined from the slope of the fitted linear equation involving cloud particle size vs. aerosol optical depth is about a factor of 2 compared to the maximum AIE value, an excellent indication of the dust aerosol indirect effect associated with cirrus cloud formation.

(2) Secondly, we conducted a study of the dust aerosol indirect effect on cirrus cloud formation based on different dust loadings. When there is no lidar data to confirm ice cloud formation associated with dust layer, we identified aerosol indirect effect by comparing the amount of cirrus clouds to different dust loadings. For this purpose, we analyzed two cases occurred in western Africa on September 23, 2006 at 1210 UTC and over Korea on March 20, 2001 at 1210 UTC. For each case, we compared the mean effective cloud particle sizes for cirrus clouds in proximity with the dust events having different loadings. For both cases, we found that the cirrus mean effective radius is smaller (larger) when more (less) dust was present, revealing dust aerosols could serve as effective ice nuclei for the formation of ice particles. Because of competition of water vapor, the presence of more dust aerosols leads to the formation of small ice particles, a theoretical hypothesis confirmed by the present observational study.

(3) Finally, we investigated the impact of dust aerosols on water and ice clouds. To compare dust aerosol indirect effects on the formation of cirrus and water clouds, we carried out a statistical analysis involving a scene over Korea occurred on April 8, 2006 at 0440 UTC, during which a significant presence of the transported dust occurred from a severe dust storm outbreak in the Gobi desert area, northern China two days before. For this case, we compared the mean effective cloud particle sizes for cirrus and water clouds with different dust loadings, and found that there is a general trend of the correlation between cloud particle size and aerosol optical depth. We demonstrate that the mean effective particle size decreases as dust optical depth increases for both ice and water clouds in accordance with the theoretical expectation. Moreover, the present dust AIE index for combined ice and water clouds is larger than AIE maximum index, revealing the significant aerosol indirect effect on cloud formation.

Some of the preceding results have been summarized and published in a refereed journal (Applied Optics, 48, 633-642; Ou, Liou, et al., 2009).

### **WRF simulation of cirrus cloud distributions**

In parallel to satellite cloud and aerosol data analysis, we also conducted a numerical study of high cloud formation employing the Weather Research Forecasting (WRF) model, designed for regional study. Our research group adopted the WRF's Version 2.2 of ARW to simulate the occurrence, evolution, and dissipation of thin cirrus clouds over the Western U.S. and Eastern Pacific, covering the ABL test flight region off the coast of southern California for the time period, March 29-30, 2007. We compared the WRF simulated cirrus cloud water content distributions to those observed by GOES and MODIS. To carry out the simulations, the model's initial and boundary conditions were extracted from NCEP-GFS (Global Forecast System) "final analysis" product, a sequence

of 6-hourly global  $1^\circ$  gridded fields based on the GFS data assimilation system. We used one of the microphysics schemes in WRF that predicts mass content and number density for each of the five forms of condensed water: cloud droplet, ice crystal, snow, graupel, and raindrop. The model simulations were performed for a 48-hour period, starting at 00Z on 29 March 2007, about 20 hours prior to ABL test flight time, and ending at 00Z on 31 March 2007. Distributions of the WRF simulated ice cloud water in terms of cloud water mixing ratio corresponding to the location of ice clouds at selected MODIS overpasses were cross checked with the cloud patterns displayed in the GOES and MODIS images.

For the purpose of comparing WRF simulations to observed cirrus cloud patterns, we acquired relevant MODIS/Terra/Aqua images for the time periods and locations of the test flights including March 29, 1830 UTC (Terra daytime), 2130 UTC (Aqua daytime), March 30, 0530 UTC (Terra nighttime), and 2045 UTC (Aqua daytime). We also collected GOES-11 visible and IR images for the dates and times of MODIS/Terra/Aqua overpasses near southern California from the NOAA website. The WRF simulated *IWP* pattern for March 29, 2200 UTC was displayed and compared with GOES 11 IR image for March 29, 2130 UTC, and MODIS RGS image and MODIS retrieved *IWP* for March 29, 2140 UTC, which included frontal and non-frontal cirrus cloud regions. All the cases were in 2007. Based on these limited comparisons, it appears that with appropriate initial and boundary conditions, WRF can be employed to produce reasonable cirrus cloud coverage and *IWP* distributions associated with both the frontal and non-frontal systems.

Additional research will be carrying out to further improve WRF for high-level cloud simulation using satellite data as boundary conditions. We anticipate that a couple of publications will result from this study.

#### Research support

The AFOSR grant supported K. N. Liou and R. Fovell, Professors of Atmospheric Sciences, S. C. Ou, Senior Research Scientist, and Y. Gu, Associate Researcher.

Respectfully submitted,



K. N. Liou

Distinguished Professor of Atmospheric Sciences and Director  
UCLA Joint Institute for Regional Earth System Science and Engineering

Cc: Lt. Col. Steven Cocks, MDA/ALWT  
Dr. Randy Lefevre  
Kristen Lund, UCLA Contract and Grant Officer  
Nancy Hom, Funds Manager, JIFRESSE